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SIMULATION METHODS OF TRANSIENT THERMAL PROCESSES IN GAS-CO
OLED REACTORS ON ANALOGUE COMPUTERS

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INTRODUCTION

Recently the analogue and digital computers are frequently used for working out complex automatic control systems,investigation of the accident and start up conditions of atomic power plants [4,5,6].The use of computers is difficult since equations for the subjects under control (in particular,a reactor,heat exchangers) are partial differential equations.

Digital computers permit partial differential equations to be solved.Complicated and long programming process of the problem is a considerable disadvantage of these machines as well as their difficult application to the inve stigation when connecting with real control system elements.

The preparation and treatment of machine equations being simple,it is not difficult for the analogue computers to connect with the real elements of control systems.Serial analogue computers (*МН*-7, *ЭМУ*-8, *ЭМУ*-10, *МН*-10, *МН*-14, *МН*-8, *МН*-*Б*) are however designed to solve usual differential equations.The method for transformation of partial equations with respect to three variables into non-linear differential equations is therefore necessary.

<u>The simulation method of transient thermal processes in gas-cooled reactors on the analogue computers.</u> As is known,transient heat transfer in fuel elements of the reactor in a general form can be presented by partial equations with respect to three variables: the radius of the fuel element,coordinates along the length and time.

A method for averaging of gas and fuel elements parameters along the radius and the reactor length is necessary.to transform this equations into ordinary differential equations.

Averaging the temperature distribution of the fuel element along the radius can be realized after introduction of the power dependence

$$T_{cr}(r) = a + br + cr^2 + \dots \tag{1}$$

for the set of equations:

$$\frac{\partial T_M}{\partial \tau} = \frac{q_{vi} S_M}{C_M \gamma_M S_M} + \frac{\alpha_r \Pi}{C_M \gamma_M S_M}(T_{Mn} - T_r) \tag{2}$$

$$\frac{\partial T_r}{\partial \tau} = \frac{\alpha_r \Pi}{C_p \cdot \gamma_r \cdot S_r}(T_{Mn} - T_r) - \frac{C_p G}{C_p \gamma_r S_r} \cdot \frac{\partial T_r}{\partial z} \tag{3}$$

where

$\overline{T}_M = T_M$, T_r =mean cross-sectional temperature of fuel element and respectively;

T_{Mn} =fuel container temperature of the gas side;

q_{vi} =heat flux per unit volume;

γ_r, C_M, γ_M =heat capacity and specific weight of gas and fuel element material,respectively;

Π, S_r, S_M =channel perimeter,cross-sectional area of gas and fuel elements;

α_r = individual heat transfer coefficient.

G = gas flow rate.

For a plane wall, δ in width,with the internal sources and one-sided heat sink with initial condition $\overline{T}_M = \int_0^\delta T_M dy/\delta$ and boundary conditions $(\lambda \frac{\partial T_i}{\partial y})_{y=0} = 0$ and $-\lambda \frac{\partial T_M}{\partial y} = \alpha_r (T_{Mn} - T_r)$,it is obtained that the thermal resistance of the wall is taken into consideration in the reduced individual heat transfer coefficient

$$\alpha_{np} = 1 / \left(\frac{1}{\alpha_r} + \frac{\delta}{3\lambda} \right) \tag{4}$$

For rod-type fuel elements of the radius r the reduced individual heat-transfer coefficient is as follows

$$\alpha_{np} = 1 / \left(\frac{1}{\alpha_r} + \frac{r}{4\lambda} \right)$$

where λ is the thermal conductivity of the fuel element materials, and the set of equations (2) and (3) becomes

$$\frac{\partial \overline{T}_M}{\partial \tau} = \frac{q_{vi} S_M}{C_M \gamma_M V_M} - \frac{\alpha_{np} \Pi}{C_M \gamma_M S_M} \cdot (\overline{T}_M - T_r) \tag{2a}$$

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$$\frac{\partial T_r}{\partial \tau} = \frac{\alpha_{np} \Pi}{C_p \gamma_r S_r} (\bar{T}_M - T_r) - \frac{C_p G}{C_p \gamma_r S_r} \frac{\partial T_r}{\partial z} \qquad (3a)$$

After averaging fuel element and gas temperatures along the radius, the heat-transfer process in the reactor, regenerator and cooler is described by partial differential equations with respect to two variables (time and the coordinate along the length)

It is necessary to find the method for determination of parameters along the reactor length. Averaging temperatures along the reactor length can be presented by the relation between the mean gas temperature and inlet and outlet temperatures

$$T_{rcp} = (T_{2p} + T_3)/2$$

In this case the core must be divided into so many sections along the reactor length that within a section the temperature could be considered linear. However, the finite difference method cannot be recommended for study of dynamics of an atomic power plant, because in this case the sets of equation of the transient heat transfer in the heater and reactor occupy a large part of the machine blocks.

Substitution of the set with distributed parameters by the set with lumpеd parameters [4,5] is the simplest and widely used method of averaging temperatures along the reactor length. This method is admissible at small diversion of the parameters from their nominal values. Accuracy of the solution is uncertain in the case of greatly changing gas flow rate, thermal capacity of the reactor and inlet gas temperature. When heat exchangers are presented by a set of equations with lumped parameters in the case of great changes of variables (start-up, heating, emergency conditions etc.) the transient process duration is distorted; the number of peculiarities of the heat transfer process is not taken into consideration.

The following averaging gas temperature method permits to obtain an admissible accuracy of simulation with a smaller number of operational amplifiers than in the case of dividing the core into the sections when the difference method is applied [7].

Gas-cooled reactor with rod-type fuel elements. Fig.1 shows the design diagram of the core with the rod-type fuel elements.

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The usual assumptions required for tstudying transient heat transfer between gas flow in the channel and the wall of the channel. with internal sources of variable heating rate are following:

1.Gas subcooling in both bottom and top reflectros is not accounted for.

2.Heat conducted in the wall along the channel is neglected.

3.Experimental individual heat-transfer coefficients of the steady-state flow is used for transient processes.

4.Heat release varies according to a cosine curve along the length of the fuel element.

With these assumptions transient heat transfer in reactor fuel elements is described by the following set of equations:

$$C_M \gamma_M S_M \frac{\partial T_M}{\partial \tau} = q_{v_0} S_M \left(\cos \pi \cdot \frac{z}{\ell + 2h}\right) \bar{N} - \alpha \cdot \Pi \cdot (T_M - T_r) \tag{2b}$$

$$C_p \cdot \gamma_r \cdot S_r \cdot \frac{\partial T_r}{\partial \tau} + C_p G \frac{\partial T_r}{\partial z} = \alpha \Pi (T_M - T_r) \tag{3b}$$

The channel centre is a zero reading along the length.

Initial and boundary conditions are:

$$z = -\ell/2 \qquad T_r(\tau, -\ell/2) = T_{2p_0} \qquad \text{at} \quad \tau = 0$$

$$z = \ell/2 \qquad T_r(\tau, \ell/2) = T_{3_0} \qquad \text{at} \quad \tau = 0$$

$$T_r(\tau, -\ell/2) = T_{2p}$$

Equations (2b),(3b) are integrated within the limits from $-\ell/2$ to $\ell/2$

$$C_M \gamma_M S_M \frac{d}{d\tau} \int_{-\ell/2}^{\ell/2} T_M(\tau, z)\, dz = q_{v_0} S_M \bar{N} \int_{-\ell/2}^{\ell/2} \cos \pi \cdot \frac{z}{\ell + 2h}\, dz - \alpha \Pi \left(\int_{-\ell/2}^{\ell/2} T_M\, dz - \int_{-\ell/2}^{\ell/2} T_r\, dz \right) \tag{6}$$

$$C_p \gamma_{rcp} S_r \frac{d}{d\tau} \int_{-\ell/2}^{\ell/2} T_r \cdot dz = \alpha \Pi \left(\int_{-\ell/2}^{\ell/2} T_M\, dz - \int_{-\ell/2}^{\ell/2} T_r\, dz \right) - C_p G (T_3 - T_{2p}) \tag{7}$$

$(1/\ell) \int_{-\ell/2}^{\ell/2} T_r(\tau, z)\, dz = T_{rcp}$ =mean gas temperature along the channel length; $(1/\ell) \int_{-\ell/2}^{\ell/2} T_M(\tau, z)\, dz = T_{Mcp}$ = mean fuel element temperature along the channel length etc.

Taking into account for these notations, equations (2b) and (3b) become of the form:

$$\frac{d T_{Mcp}}{d\tau} = \frac{2 q_{v_0} V_M}{C_M \gamma_M V_M} \cdot \frac{\ell + 2h}{\pi \ell} \left(\sin \pi \cdot \frac{\ell/2}{\ell + 2h} \right) \bar{N} - \frac{\alpha F}{C_M \gamma_M V_M} (T_{Mcp} - T_{rcp}) \tag{6a}$$

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$$\frac{dT_{rcp}}{d\tau} = \frac{\alpha F}{C_p \gamma_{rcp} \cdot V_r}\left(T_{Mcp} - T_{rcp}\right) - \frac{C_p G}{C_p \gamma_{rcp} V_r}\left(T_3 - T_{2p}\right) \tag{7a}$$

where

v = volume of fuel elements or gas per fuel element;

F = heat transfer surface of fuel elements;

Thus for mean temperatures of the gas T_{rcp} and wall T_{Mcp}, ordinary non-linear differential equations are obtained. The analogue computers can be used for their solution.

Let us apply integration by parts within the limits from $-\ell/2$ to $\ell/2$ to integral of the form $\int_{-\ell/2}^{\ell/2} T_r(\tau,z)\,dz$ to obtain the relation between the mean gas temperature T_{rcp} and the inlet T_{2p} and outlet T_3 gas temperatures. As a result of successive integration, the integral can be represented by the infinite series

$$T_{rcp} = \frac{1}{\ell}\int_{-\ell/2}^{\ell/2} T_r(\tau,z)\,dz = \frac{z}{\ell}T_r - \frac{z^2}{2\ell}\frac{\partial T_r}{\partial z} + \frac{z^3}{6\ell}\frac{\partial^2 T_r}{\partial z^2} - \frac{z^4}{24\ell}\frac{\partial^3 T_r}{\partial z^3} + \frac{z^5}{120\ell}\frac{\partial^4 T_r}{\partial z^4} - \ldots\ldots \Big|_{-\ell/2}^{\ell/2}$$

Infinite series (8) may be presented by the general term of the series:

$$T_{rcp} = \sum_{1}^{\infty}\left(\frac{z^n}{n!}\right)\frac{\partial^n T_r}{\partial z^n}(-1)^{n+1} \tag{8a}$$

For this kind of series uniform convergence takes place, if the series $\sum_1^\infty \frac{z^n}{n!}$ converges uniformly to the set z, and the function $\frac{\partial^n T_r}{\partial z^n}$ (at any z and n) forms the monotonous sequence and at any z and n is limited

$$\left|\frac{\partial^n T_r}{\partial z^n}\right| \le K$$

B.. the power series converge at any z (the convergence radius $R=\infty$) /1 - 3/.

The function $T_r(\tau,z)$ is continuous within this series integration limits $-\ell/2$ $+\ell/2$. Derivatives along the coordinate z $T_r(\tau,z)$ are limited as the heat flux and mean gas temperature are finite (integral (8)). Therefore infinite series (8) is uniformly convergent one, and the solution of the problem may be represented by a few terms of the series expansion of T_r.

(a) One term of series expansion.

$$T_{rcp} = \frac{z}{\ell}T_r\Big|_{-\ell/2}^{\ell/2} = \frac{1}{2}\left(T_{2p} + T_3\right) \tag{8b}$$

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Hence $T_3 = 2\,T_{rcp} - T_{2p}$

A set of equations:

$$\frac{dT_{Mcp}}{d\tau} = \frac{2q_{vo}V_M}{C_M\gamma_M S_M}\,\frac{\ell+2h}{\pi\ell}\left(\sin\pi\frac{\ell/2}{\ell+2h}\right)\bar{N} - \frac{\alpha F}{C_M\gamma_M S_M}\left(T_{Mcp} - T_{rcp}\right) \qquad (6a)$$

$$\frac{dT_{rcp}}{d\tau} = \frac{\alpha F}{C_p\gamma_{rcp}V_r}\left(T_{Mcp} - T_{rcp}\right) - \frac{C_p G}{C_p\gamma_{rcp}V_r}\left(T_3 - T_{2p}\right) \qquad (7a)$$

$$T_3 = 2\,T_{rcp} - T_{2p}\,.$$

(b) Two terms of series expansion

$$T_{rcp} = \frac{z}{\ell}T_r - \frac{z^2}{2\ell}\cdot\frac{\partial T_r}{\partial z} + \dots\Big|_{-\ell/2}^{\ell/2} = \frac{1}{2}(T_{2p}+T_3) - \frac{\ell}{8}\left[\left(\frac{\partial T_r}{\partial z}\right)_3 - \left(\frac{\partial T_r}{\partial z}\right)_{2p}\right] \qquad (8b)$$

The values $\ell\left(\frac{\partial T}{\partial z}\right)_3$ and $\ell\left(\frac{\partial T}{\partial z}\right)_{2p}$ are obtained from equation (3b):

$$\ell\left(\frac{\partial T_r}{\partial z}\right)_3 = \frac{\alpha F}{C_p G}\left(T_{M3} - T_3\right) - \frac{C_p\gamma_{r3}V_r}{C_p G}\frac{dT_3}{d\tau}$$

$$\ell\left(\frac{\partial T}{\partial z}\right)_{2p} = \frac{\alpha F}{C_p G}\left(T_{M2} - T_{2p}\right) - \frac{C_p\gamma_{r2}V_r}{C_p G}\frac{dT_{2p}}{d\tau}$$

$$T_{rcp} = \frac{1}{2}\left(T_{2p} + T_3\right) - \frac{1}{8}\left[\frac{\alpha F}{C_p G}\left(T_{M3} - T_3 - T_{M2} + T_{2p}\right) - \frac{C_p\gamma_{r3}V_r}{C_p G}\left(\frac{dT_3}{d\tau} - \frac{\gamma_{2p}}{\gamma_3}\frac{dT_{2p}}{d\tau}\right)\right]$$

Hence

$$\frac{dT_3}{d\tau} = \frac{\gamma_{2p}}{\gamma_3}\frac{dT_{2p}}{d\tau} + 8\frac{C_p G}{C_p\gamma_3 V_r}\left(T_{rcp} - \frac{T_{2p}+T_3}{2}\right) + \frac{\alpha F}{C_p\gamma_3 V_r}\left(T_{M3} - T_3 - T_{M2} + T_{2p}\right)$$

The set of equations is obtained:

$$\frac{dT_{Mcp}}{d\tau} = \frac{2q_{vo}V_M}{C_M\gamma_M V_M}\cdot\frac{\ell+2h}{\pi\ell}\left(\sin\pi\frac{\ell/2}{\ell+2h}\right)\bar{N} - \frac{\alpha F}{C_M\gamma_M V_M}\left(T_{Mcp} - T_{rcp}\right) \qquad (6a)$$

$$\frac{dT_{rcp}}{d\tau} = \frac{\alpha F}{C_p\gamma_{rcp}V_r}\left(T_{Mcp} - T_{rcp}\right) - \frac{C_p G}{C_p\gamma_{rcp}V_r}\left(T_3 - T_{2p}\right) \qquad (7a)$$

$$\frac{dT_3}{d\tau} = \frac{\gamma_{2p}}{\gamma_3}\frac{dT_{2p}}{d\tau} + 8\frac{C_p G}{C_p\gamma_3 V_r}\left(T_{rcp} - \frac{T_{2p}+T_3}{2}\right) + \frac{\alpha F}{C_p\gamma_3 V_r}\left(T_{M3} - T_3 - T_{M2} + T_{2p}\right) \qquad (10)$$

$$\frac{dT_{M3}}{d\tau} = \frac{q_{vo}\cdot V_M}{C_M\gamma_M V_M}\cdot\left(\cos\pi\frac{\ell/2}{\ell+2h}\right)\bar{N} - \frac{\alpha F}{C_M\gamma_M V_M}\left(T_{M3} - T_{2p}\right) \qquad (11)$$

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$$\frac{dT_{Mz}}{d\tau} = \frac{q_{v_0} V_M}{C_M \gamma_M V_M}\left(\cos\pi\frac{e/2}{e+2h}\right)\bar{N} - \frac{\alpha F}{C_M \gamma_M V_M}\left(T_{Mz} - T_{2p}\right) \qquad (12)$$

(c) Three terms of series expansion

$$T_{rcp} = \frac{z}{e}T_r - \frac{z^2}{2e}\frac{\partial T_r}{\partial z} + \frac{z^3}{6e}\cdot\frac{\partial^2 T_r}{\partial z^2} - \cdots \Big|_{-e/2}^{e/2} \qquad (8d)$$

The second derivatives of the temperature are determined by equation (3b)

$$\frac{\partial^2 T_r}{\partial z^2} = \frac{\alpha\Pi}{C_p G}\left(\frac{\partial T_M}{\partial z} - \frac{\partial T_r}{\partial z}\right) - \frac{C_p \gamma_r S_r}{C_p G}\cdot\frac{\partial^2 T_r}{\partial z \cdot \partial \tau}$$

Since the function $T_r(\tau, z)$ is continuous, has all kinds of partial derivatives (they are also continuous) and is defined within the open range $-e/2 + e/2$, the following relation is valid:

$$\frac{\partial^2 T_r}{\partial z \cdot \partial \tau} = \frac{\partial^2 T_r}{\partial \tau \cdot \partial z}$$

Let us denote $e\left[\left(\frac{\partial T_r}{\partial z}\right)_{2p} + \left(\frac{\partial T_r}{\partial z}\right)_3\right] = T'_{rz}$; $e\left[\left(\frac{\partial T_M}{\partial z}\right)_{2p} + \left(\frac{\partial T_M}{\partial z}\right)_3\right] = T'_{Mz}$

Where now T'_{rz} and $T'_{Mz} = f(\tau)$

Substitution of integration limits (into equation (8d) and simple transformations yield

$$T_{rcp} = \frac{1}{2}\left(T_{2p} + T_3\right) - \frac{1}{8}\left[\frac{2\alpha F}{C_p G}\left(T_{M3} - T_3\right) - 2\frac{C_p \gamma_{r3} \cdot V_r}{C_p \cdot G}\cdot\frac{dT_3}{d\tau} - T'_{rz}\right] + \frac{1}{48}\left[\frac{\alpha F}{C_p G}\left(T'_{Mz} - T'_{rz}\right) - \frac{C_p \gamma_{rcp} V_r}{C_p G}\cdot\frac{dT'_{rz}}{d\tau}\right] \qquad (8e)$$

The set of equations: $$\frac{dT'_{Mz}}{d\tau} = -\frac{\alpha F}{C_M \gamma_M V_M}\left(T'_{Mz} - T'_{rz}\right) \qquad (13)$$

$$\frac{dT'_{rz}}{d\tau} = 12\frac{dT_3}{d\tau} + \frac{C_p G}{C_p \gamma_{rcp} V_r}\cdot\left[48\left(\frac{T_{2p}+T_3}{2}\right) - T_{rcp} + \frac{1}{8}T'_{rz}\right] - \frac{\alpha F}{C_p \gamma_{rcp} V_r}\left[12\left(T_{M3} - T_3\right) - \left(T'_{Mz} - T'_{rz}\right)\right] \qquad (14)$$

$$\frac{dT_3}{d\tau} = -\frac{\gamma_{2p}}{\gamma_3}\cdot\frac{dT_{2p}}{d\tau} + \frac{\alpha F}{C_p \gamma_{r3} V_r}\left(T_{M3} - T_3 + T_{Mz} - T_{2p}\right) - \frac{C_p G}{C_p \gamma_{r3} V_r}T'_{rz} \qquad (15)$$

$$\frac{dT_{rcp}}{d\tau} = \frac{\alpha F}{C_p \gamma_{rcp} V_r}\left(T_{Mcp} - T_{rcp}\right) - \frac{C_p G}{C_p \gamma_{rcp} V_r}\left(T_3 - T_{2p}\right) \qquad (7a)$$

$$\frac{dT_{Mcp}}{d\tau} = 2\frac{q_{v_0}\cdot V_M}{C_M \gamma_M V_M}\cdot\frac{e+2h}{\pi e}\left(\sin\pi\frac{e/2}{e+2h}\right)\bar{N} - \frac{\alpha F}{C_M \gamma_M V_M}\left(T_{Mcp} - T_{rcp}\right) \qquad (6a)$$

$$\frac{dT_{M3}}{d\tau} = \frac{q_{v_0} V_M}{\gamma_M \cdot C_M \cdot V_M}\left(\cos\pi\frac{e/2}{e+2h}\right)\bar{N} - \frac{\alpha F}{C_M \gamma_M V_M}\left(T_{M3} - T_3\right) \qquad (11)$$

$$\frac{dT_{Mz}}{d\tau} = \frac{q_{v_0} V_M}{C_M \gamma_M V_M}\left(\cos\pi\frac{e/2}{e+2h}\right)\bar{N} - \frac{\alpha F}{C_M \gamma_M V_M}\left(T_{Mz} - T_{2p}\right) \qquad (12)$$

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Analogous sets of equations may be written for 4,5 etc terms of series expansion.

Results of electronic simulation of transient heat-transfer equations. The above suggested method permits to describe the transient heat-transfer process in apparatuses with various accuracy depending on a number of the terms of the series expansion. A larger number of terms of the series expansion suggests more accurate mathematic description of the process. However, we obtain the set of differential equations of a higher order that leads to a sharp increase of simulating apparatuses. The investigation of transient heat-transfer process in a gas-cooled reactor under various external perturbations in case of one, two and three terms of the series expansion was carried out on the analogue computer of the type 1 wiht the aim to choose an optimal number of terms of the series expansion. Reactor kinetics have been described by known equations (4) taking into account the six groups of the delayed neutrons

$$\frac{dn}{d\tau} = \frac{\Delta k - \beta}{\ell^*} n + \sum_{i=1}^{6} \lambda_i C_i$$

$$\frac{dC_i}{d\tau} = -\lambda_i C_i + \frac{\beta_i}{\ell^*} n$$

where

n=the neutron density

Δk=the reactivity

β_i= the delayed-neutron fraction of the i-group in the total number of neutrons

λ_i= the decay constant of source of i-group delayed neutron

C_i = the concentration of nuclei-delayed neutron emitters

ℓ^* =mean neutron life-time.

The effective life-time $l^*=10^{-5}$sec and zero temperature coefficient for both the fuel and the moderator of the gas-cooled reactor were assumed.

Verification of the method proposed was carried out for gas-cooled reactor of an atomic energy plant 50 Mwt in power with rod-type fuel elemtns. The coolant was nitrogen. Fuel elements composition UO_2+BeO, moderator was BeO, fuel element coatings were stainless steel alloys.

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The estimation of the accuracy of the relation T_{rcp} in terms of inlet and outlet temperatures and their derivatives along the coordinate z by means of various numbers of tams of the series expansion of T_{rcp} at stationary and transient conditions for the gas-cooled reactor of the atomic energy plant N_t= 50 Mwt was made.

The estimation of the error of the truncated series can be made with sufficient accuracy by the first term of this series (1).

In the steady state case the accuracy of the series expansion of the relation T_{rcp} in terms of the inlet and outlet temperatures and their derivatives can be estimated in the nominal regime.As calculations showed,two terms of the series expansion provided sufficient accuracy in the steady-state case (the error was 1-3 per cent).

The transient conditions of a gas-cooled reactor N_t= 50Mwt have been stodied on the analogue computers of type MH6 -1 when T_{rcp} was presented in terms of inlet and outlet temperatures by various number of terms of the series expansion and by the finite difference method.

Analogue computer MH6 -1 is a block-type arrangement.Operational amplifiers of this computer have the automatic stabilization of zero level (the modulation-demodulation channel) and,thus,the little outlet drift (40-60 mkv for 10 min)The frequency responce of the amplifier is linear in inverted regime to a frequency of 1000 c/sec.Constant coefficients are given by the compensating method with an error of 0.2 per cent. Recording of the resulta is made on the electronic automatic potentiometer;the frame passes the whole scale for 1 sec.The static error of the recorder is 0.5 per cent.

For a gas-cooled reactor on an analogue computer MH6-1 the discontinuous and sinusoidal disturbances separate in each parameter have been considered at various numbers of term of the series expansion intransient heat-transfer equation to determine the limits of validity of this method and the required number of series terms.The results obtained are illustrated in Fig.s 2-6.

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Fig.2 shows the outlet gas temperature change of the reactor with the discontinuous inlet gas temperature drop by 100^0. Two and three terms of the series expansion give practically the same values flask-ups of the inlet gas temperature. One term of the series expansion causes 5-fold excees of the outlet gas temperature flask-up. with such disturbances.

Figs. 4 and 3 show the change of the neutron power of the reactor and outlet gas temperature at discontinuous decrease of mass gas flowrate to $G = 0.25\ G_0$. Flash-ups of the outlet gas temperature T_{2p} practically coincide with two and three terms of series expansion. The outlet reactor gas temperature flask-up is overextimated 1.4-1.5-fold with one term of the series expansion T_{rcp} .

Under dropping of the safety rods and constant mass-flow rate of a gas and inlet gas temperature of the reactor, the curves of the transient process dor all variables $(n, T_{Mcp}, T_3, T_{rcp})$ show a good agreement with each other with 1,2,3 terms of the series expansion T_{rcp}. The mean metal temperature change in this case is shown in Fig.5. Under the reactivity disturbance, the transient heat-transfer process may be described by equation with one term of T_{rcp} expansion in terms of inlet and outlet temperatures.

The following dunamic characteristics of a gas-cooled reactor with a complex of perturbations were studied after researching of individual influence of the disturbances ΔG, ΔT_{2p}, Δk to estimate the accuracy of representation of the transient heat-transfer equations by one, two or three terms of the series expansion:

1. The deep change of the reactor heat power ($\Delta k = -0.005$)
2. Discontinuous decrease of the mass-flow rate of a gas $\Delta G = 0.75 G_0$.
3. Constant discontinuous temperature drop by 100^0C or 50^0 increase of inlet gas temperature.

The result of simulation have shown that expression of T_{rcp} in terms of T_{2p} and T_3 by one term of the series expansion under such xomplex disturbances gives essential excess of flask-up of the outlet reactor-gas temperature and 1.3-1.5-fold underestimation of the duration of transient process in comparison with the real values.

Two terms of series expansion of T_{rcp} in terms of T_{2p} and T_3

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and their derivatives along the coordinate z provide sufficient accuracy of the solution under reactor transient conditions (error is 3-4 per cent).

The same system with the complex perturbation have been solved numerically by the finite difference method. The results of this solution are the criterion of corect simulation of the transient heat-transfer equations with various numbers of the T_{rcp} series expansion terms. In the finite difference method, the reactor fule-element length is broken into a few sections. The linear temperature profile is assumed within each section.

The channel length is broken into a few sections, the number of which is chosen depending on the required accuracy of the solution (2,4,6 sections). The results of simulation have shown that division of the fuel element length into 4 sections provides sufficient accuracy of the solution (error is not more than 1-3 per cent). The points of control numerical solution by the finite difference method are plotted in Fig.6 which gives a close agreement with the curves of the solutions for 2 and 3 terms of the series expansion.

CONCLUSION

The proposed method of simulation of transient heat-transfer processes in a gas-cooled reactor on the analogue computer takes into account parameter distribution along the reactor length by the expression of the integral-mean gas temperature in terms of inlet and outlet temperatures and their derivatives as several terms of the series expansion.

The method proposed is verified with deep separate and simultaneous disturbances of the gas flow-rate, heat power and inlet gas temperature. For a gas-cooled reactor of an atomic power plant two terms of series expansion provide sufficient accuracy of the dolution (error is not more than 3-4 per cent).

The method proposed is compared with another simulation method - the finite difference method- taken as a reference one and it is shown that the methos presented is more economic than the finite difference one (the reactor is described by 5 differential equations in comparison with 8 equations in the finite difference method).

This method may be used for study of dynamic characteristics of a reactor with energy change, heating-up starting-up and reac-

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tor shut-down cooling.

The method may be effectively used for study of the dynamic characteristics of a regenerator,cooler and other heat exchangers of nuclear power plants.

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FIGURES

Fig.1 Calculation shceme of the reactor core

Fig.2 Outlet gas temperature variation with jump of inlet temperature by 100°C.

Fig.3. Plot of the neutron power with jump of gas-flow rate by $G = 0.25\ G_0$.

Fig.4 Plot of the outlet gas temperature with jump of gas-flow rate to $G = 0.25\ G_0$

Fig.5 Plot of the mean metal temperature with dropping of safety rods ($\Delta k = -0.015$).

Fig.6 Plot of the outlet gas temperature with simultaneous change of the flow-rate and reactivity ($\Delta G = 0.75\ G_0$; $\Delta k = -0.005$)

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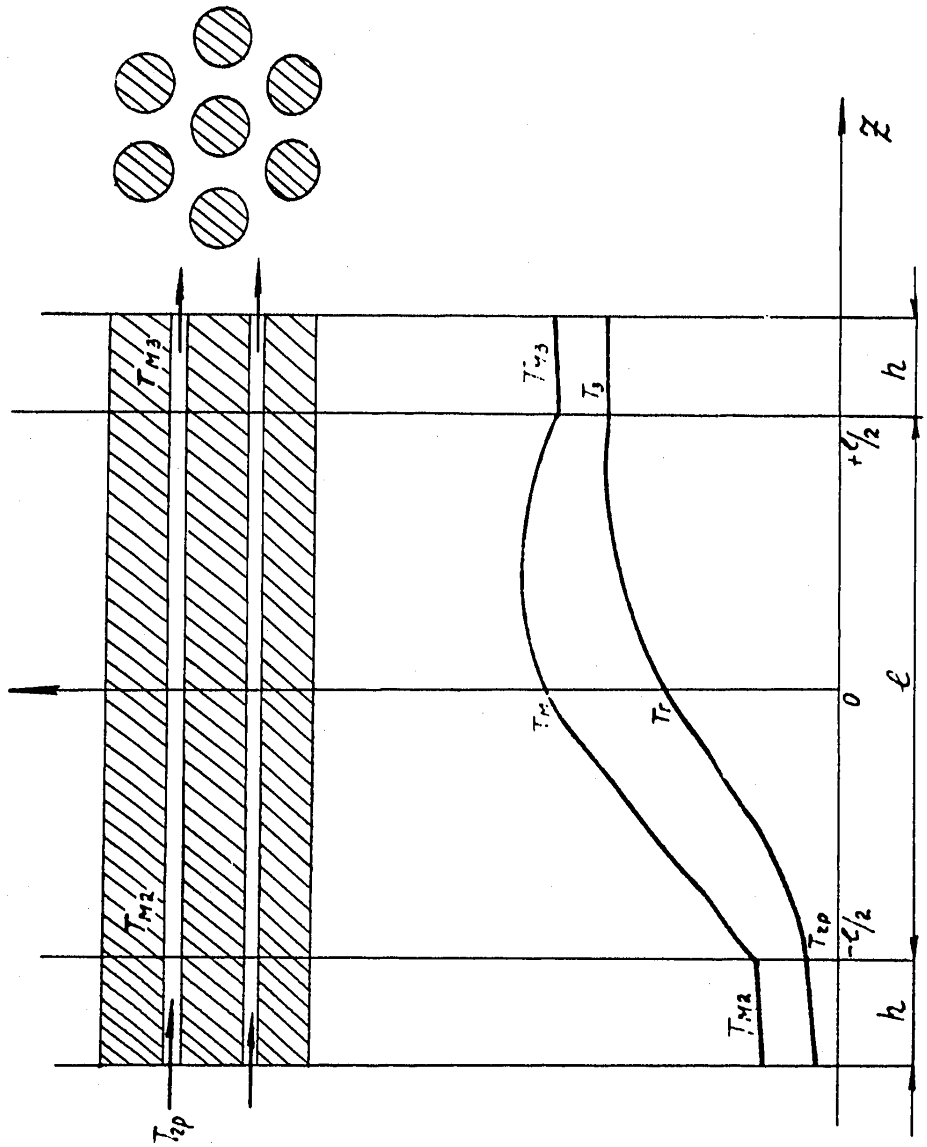

Fig. 1

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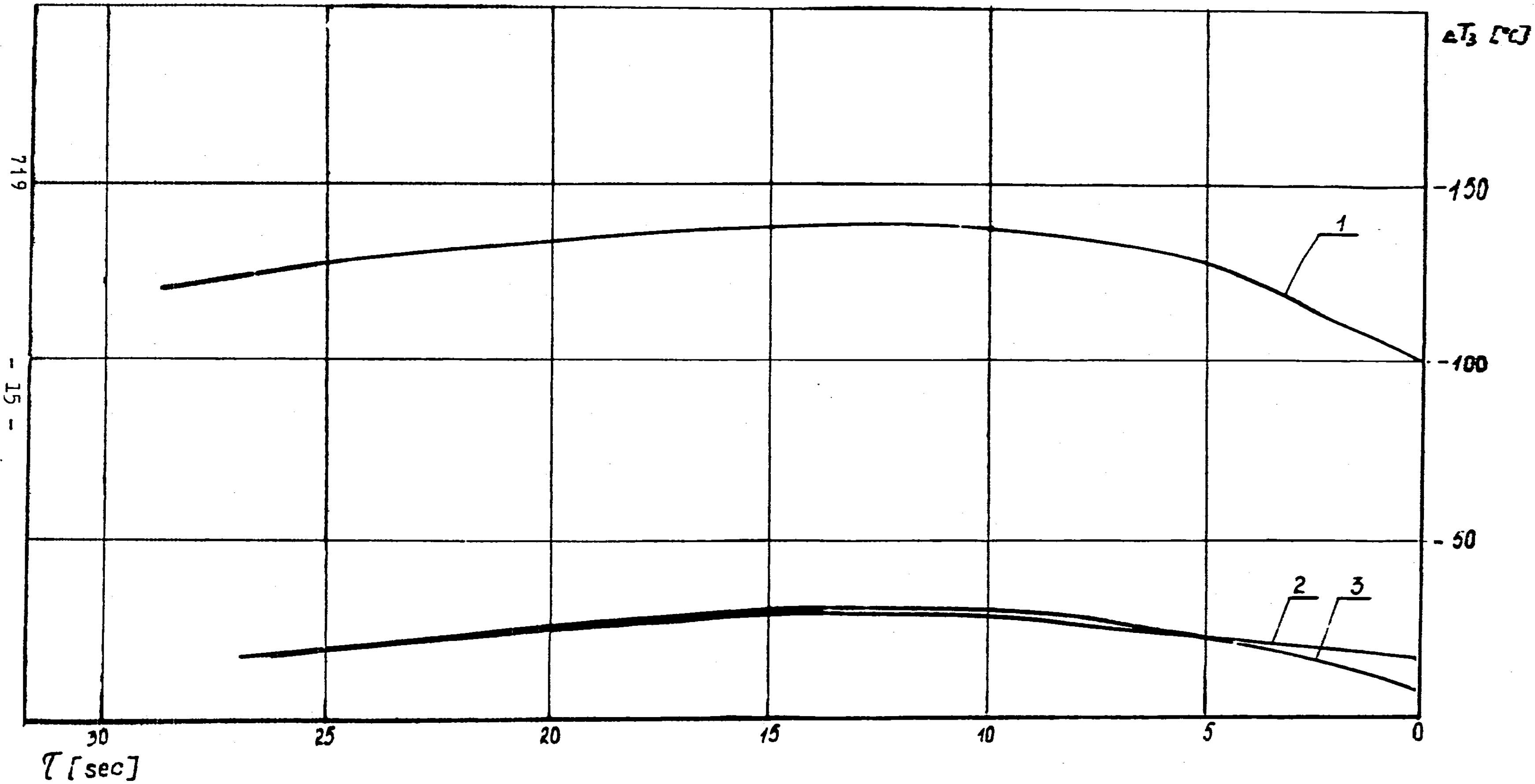

Fig . 2

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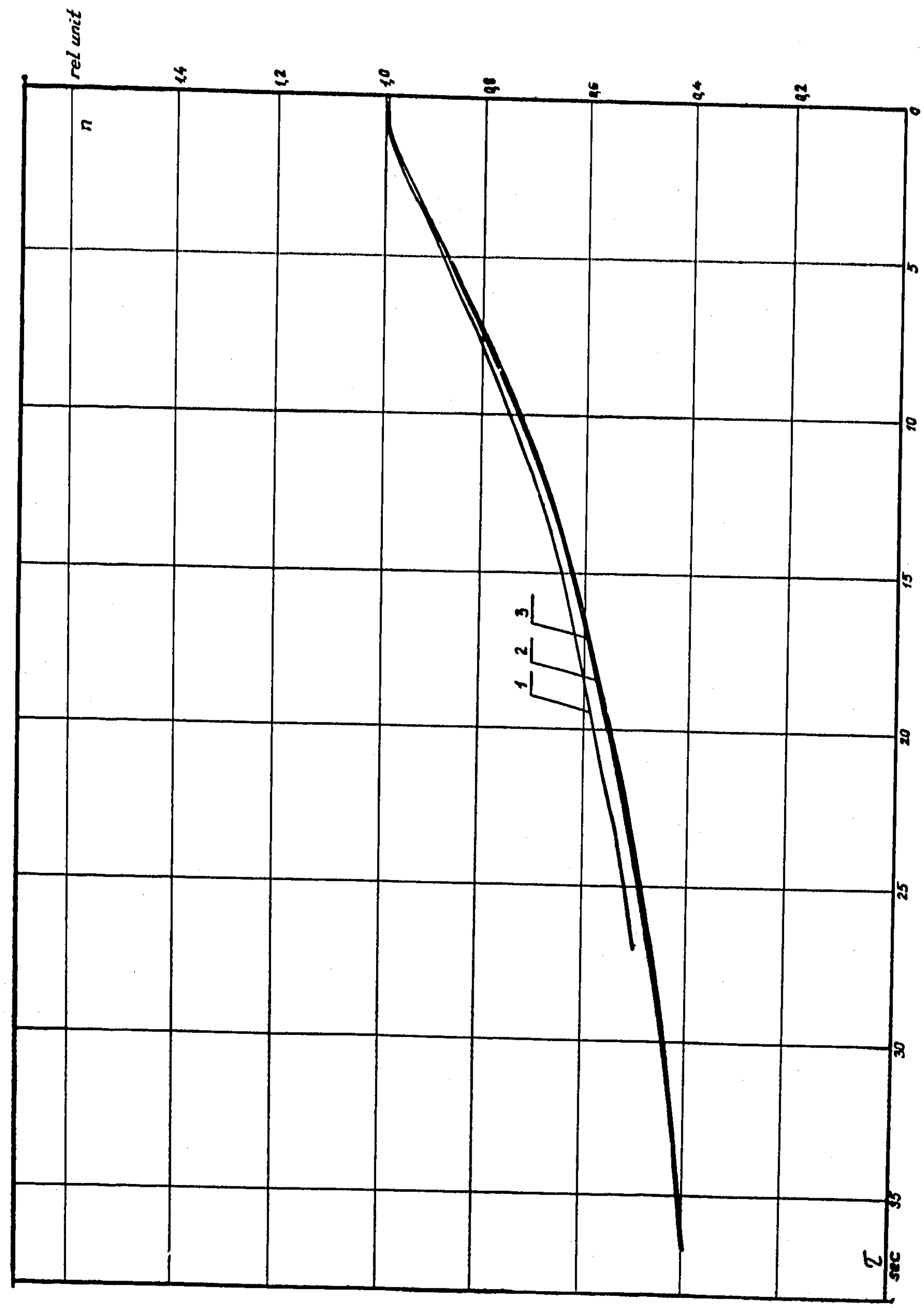

Fig. 3

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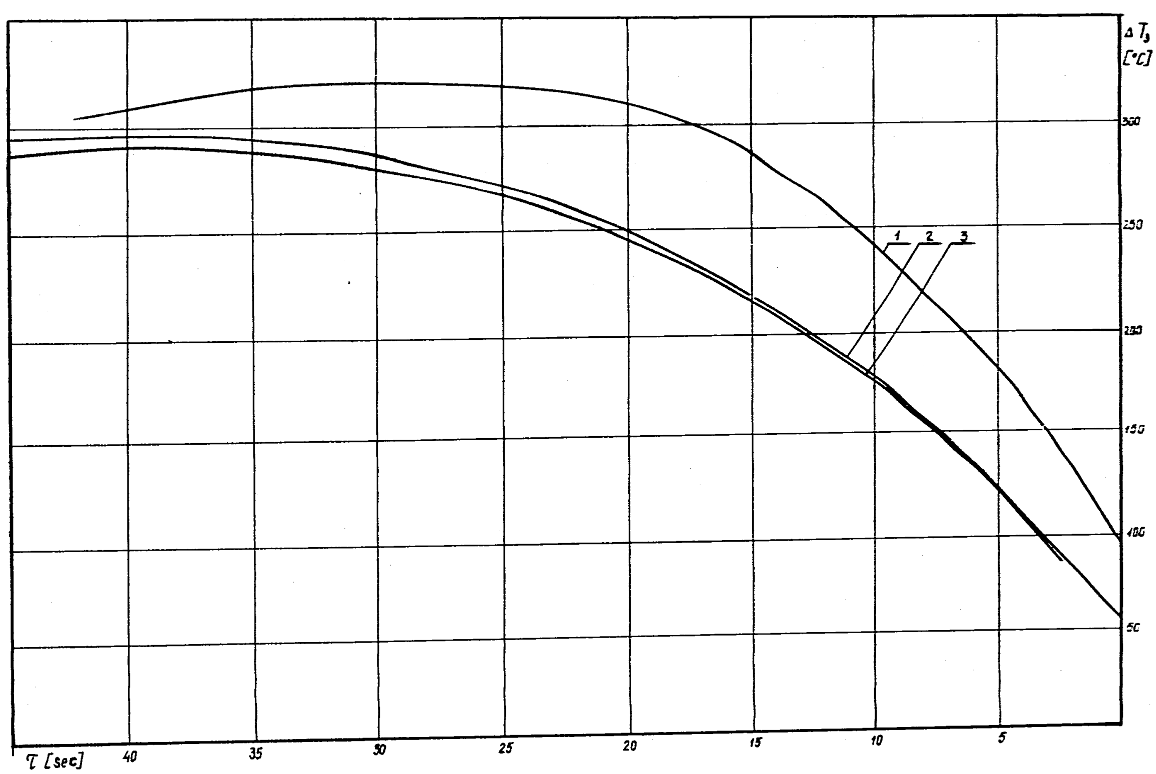

Fig. 4

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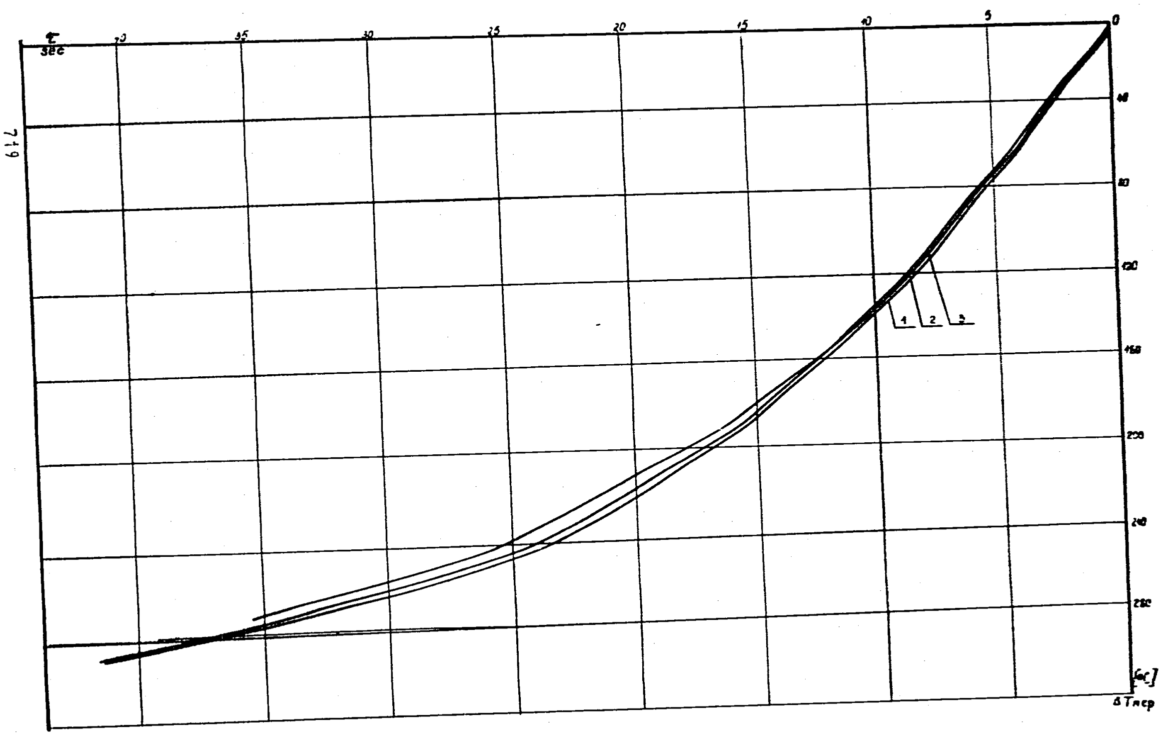

Fig. 5

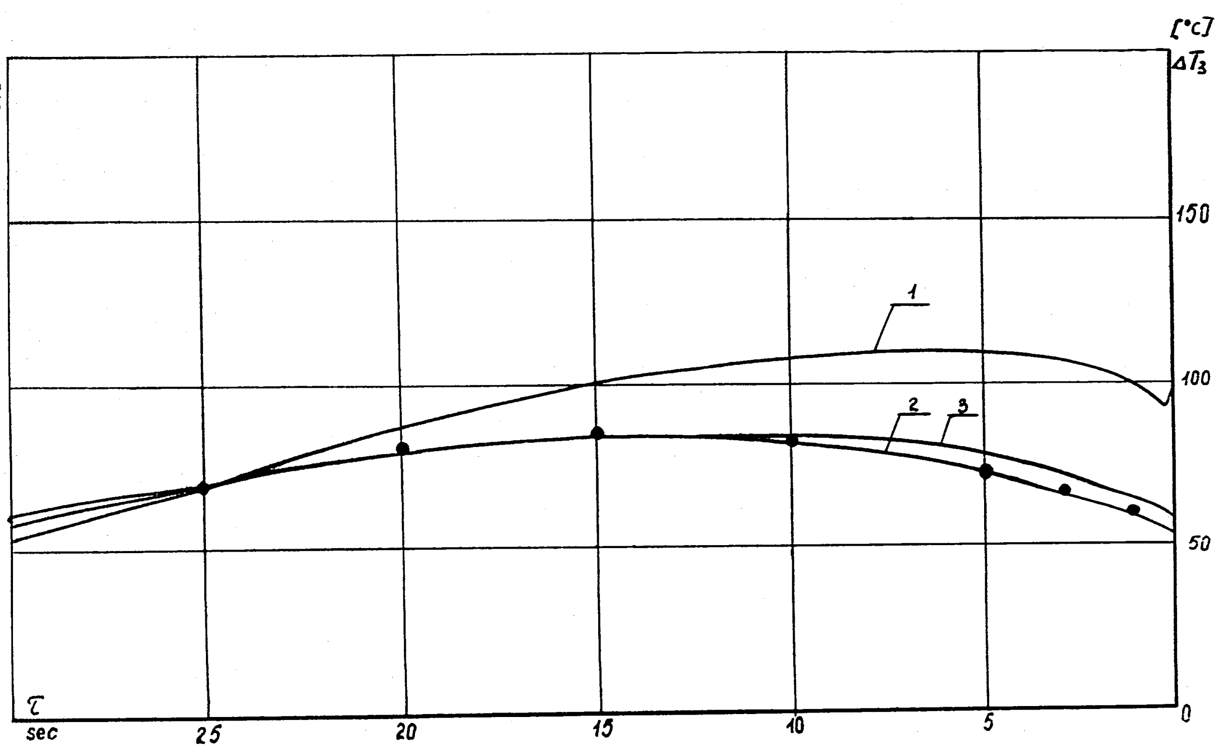

Fig. 6

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